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Photovoltaic-Integrated Electrochromic Device for Smart-Window Applications

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PHOTOVOLTAIC-INTEGRATED ELECTROCHROMIC DEVICE FOR SMART-WINDOW APPLICATIONS

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ABSTRACT

Three different, innovative approaches have been taken to develop photovoltaic (PV) integrated electrochromic (EC) devices for smart-window applications. These are (i) a stand-alone, side-by-side PV-powered EC window; (ii) a monolithically integrated PV-EC device; and, (iii) a novel photoelectrochromic device based on dye-sensitized TiO_2 solar cells. The compatibility of PV-EC devices has been analyzed and the potential for large energy savings for building applications has been suggested.

KEYWORDS

Smart windows, photovoltaics, electrochromics, silicon-carbon alloys, dye-sensitized TiO_2

INTRODUCTION

A smart material, by its very definition, implies that it has the ability to sense or respond to an external stimulus in a predetermined and controllable manner. The primary function of a glass, particularly for architectural applications, is to transmit light. A smart-window glass would be one in which its light transmission properties can be changed in response to an external stimulus such as light, heat, or electrical impulse. Well-known examples are photochromic, thermochromic, and electrochromic glasses. An electrochromic (EC) smart window, therefore, will be one in which the light transmission properties can be changed in a controlled and reversible manner when an electric current flows through the device. In recent years, we have seen some major innovations in window technologies. For example, the use of spectrally selective low-E coating on window glass has made a major impact in energy savings. But this is a passive technology. However, the electrochromic smart window, for the first time, provides the dynamic control that enables one to utilize the energy exchange through a window in a controlled way and to maximize the energy savings. Windows are the major source of energy loss or gain in a building envelope.

An electrochromic smart window (ESW) can offer unprecedented benefit to the end user and at the same time offer enormous energy savings. One of the benefits of the ESW in a building envelope is that by controlling the amount of light, it uses sunlight more effectively and thereby reduces the lighting expense. Also, better use of the functionality of a window can reduce a building's energy use in the following way: 25% of heating and cooling needs, 50% of lighting, and 30% of peak power demand. Enormous savings are possible for both residential and commercial buildings in both new and retrofit window applications in virtually all U.S. climates. This technology can displace nearly 1500 megawatts/year in new electric power-generation requirements, which amounts to approximately 1.5 quads/year or nearly $15 billion/year of energy savings. A large fraction of the approximately 2 billion square meters of building windows in the United States alone could benefit from the use of a solar-control device such as an EC-smart window. A retrofit EC-smart window with no external wiring and power source could be the most desirable option. An integrated photovoltaic-powered (PV-EC) window is the obvious choice, particularly since PV technology is making a strong inroad in building facades. Moreover, as will be discussed later, the operational characteristics of both PV and EC technologies are mutually compatible. A small area of PV cells can provide sufficient electric power to operate a large-area EC window. In this paper, a brief overview of both EC and PV technologies and their integration to fabricate a self-powered electrochromic smart window will be given.

ELECTROCHROMIC SMART WINDOWS (ESW)

Electrochromic phenomena consists of reversible changes in the optical properties (transparent ↔ absorbing/reflecting) of a given material induced by an externally applied electric field or current. The electrochromic (EC) effect was first discovered in thin films of certain transition metal oxides, such as M_0O_3, and WO_3, in late 1960s (Deb, 1969). Because of its superior optical and electrical properties, WO_3 is the preferred material for EC devices. A typical EC device, shown in Figure I, consists of a thin

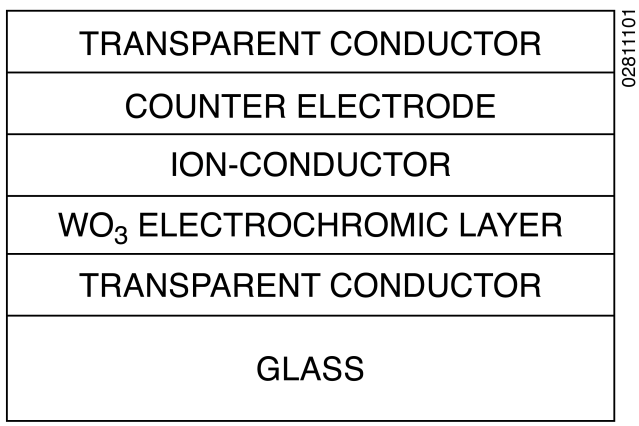

Figure 1. A typical electrochromic device

film of EC material (WO_3) an ion storage layer (IS), and an ion conducting layer (IC) sandwiched between two transparent conducting oxide (TCO) layers. The entire device structure in its unactivated state is optically clear and transmits about 70% to 80% of the incident light. On applying a small dc voltage (1-3 volts) across the device, the light transmission properties can be changed in the entire visible and near-infrared region to nearly zero transmittance level in one mode of polarity. It will remain in that state for a prolonged period of time, up to many hours, without any applied voltage. On reversing the polarity, the device will return to its original transparent state. Although there is still controversy about details of the coloration mechanism, it is generally accepted that it is due to simultaneous injection and extraction of electrons and light metal ions (H^+, Li^+…..) into the oxide layer according to the reaction scheme: WO_3 (colorless) + $xM^+ + xe^- \leftrightarrow M_xWO_3$ (blue). The performance characteristics of an EC device is a function of device parameters, but generally falls within the range specified in Table I.

Table I.

Performance Characteristics of an EC Device

Optical transmittance	
visible – near IR	1.0% to 80%
Switching voltage	0.5 – 3.0 volts
Total injected charge	up to 50 mc
Switching time	100 m sec to 60 sec
Memory	1 – 24 hours
Cyclic lifetime	10K – 5M cycles
Projected lifetime	up to 20 years
Operating temperature	-30°c to 70°c
Total thickness of coatings	~2µ

The construction of an ESW is schematically shown in Figure 2(a). The design features can incorporate other window innovations such as low-E coating, AR-filling, and vacuum insulation to achieve the ultimate energy saving features in a window technology. The spectral characteristics of a typical ESW in the colored and bleached state are shown in Figure 2(b). The durability of ESW is a key issue and remains under intense investigation. Sage Electronics has reported accelerated life testing results that show over 85,000 cycles without degradation. Similarly, OCLI has reported up to 70,000 cycles at 25°C with no change in performance (O'Brien et al., 1999). We at NREL, have tested ESW in our accelerated life testing set-up and achieved over 60,000 cycles under different test conditions without significant degradation.

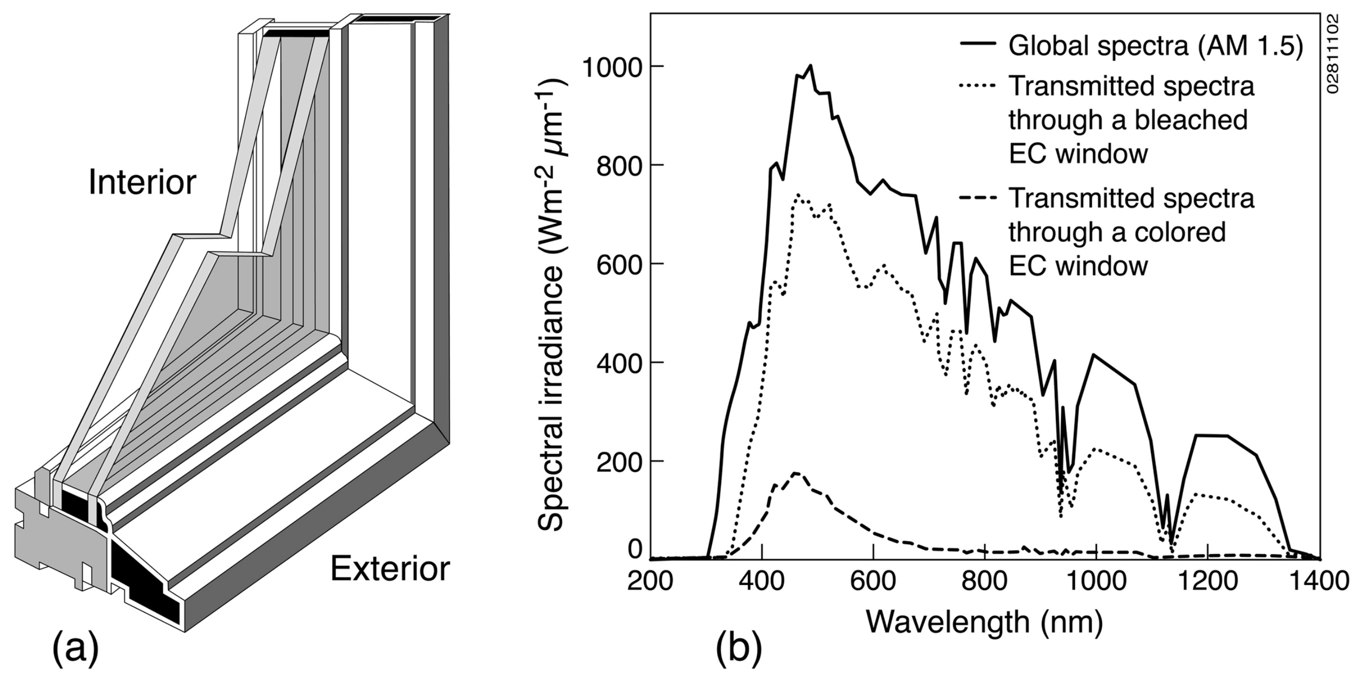

Figure 2. (a) Schematic diagram of an electrochromic smart window, (b) Spectral characteristics of a typical electrochromic window

PHOTOVOLTAIC-POWERED EC-WINDOWS (PV-EW)

The idea of combining a photoconductive and electrochromic device (PC-EC) was first explored for an electrophotographic application (Deb, 1969). An extension of that idea that incorporates a PV device with an EC device becomes even more compelling because the PV systems are increasingly being used in building facades (Benson et al., 1995). The striking energy savings advantage of a PV-ECW can be illustrated in the following way: a 1 KW_p pv-power can remove approximately 3.0 kW_p of heat from a building envelope, and the same 1kWp of PV used to activate a PV-ECW can avert ~110 KW_p, resulting in an enormous energy savings.

Two possible PV-ECW geometries have been considered. The first is a side-by-side geometry, in which the window frame is covered with solar cells; the second is a monolithic design, in which the EC layers are deposited on top of the PV-layers. The working of a side-by-side prototype PV-ECW device, although relatively straightforward, was reported earlier (Bechinger et al., 1996).

The monolithic, tandem PV-ECW device [see Figure 3(a) and (b)] requires a transparent PV coating that still outputs enough voltage to drive the EC device and enough current to operate the device at a reasonable speed. For the EC device currently employed, a 25 mC/cm^2 charge is required to finish a coloring or bleaching process. To color the window in 5 min requires only about 0.1 mA/cm^2 current density from the PV device. This gives room to increase the band gap and reduce the thickness of a standard territorial PV device in order to gain additional transparency.

Although there is a considerable body of research on wide-bandgap silicon-carbon alloys, we believe this is the first project to utilize a semitransparent solar cell made entirely of a-SiC:H material (Bullock et al., 1996). The main technical challenge lies in reducing the thickness of the device to less than 100 nm for semitransparency. When semitransparent PV devices become very thin, the top contact may short the PV device more easily and render the PV-ECW stack useless. This problem has made the fabrication of monolithic PV-ECW devices very challenging.

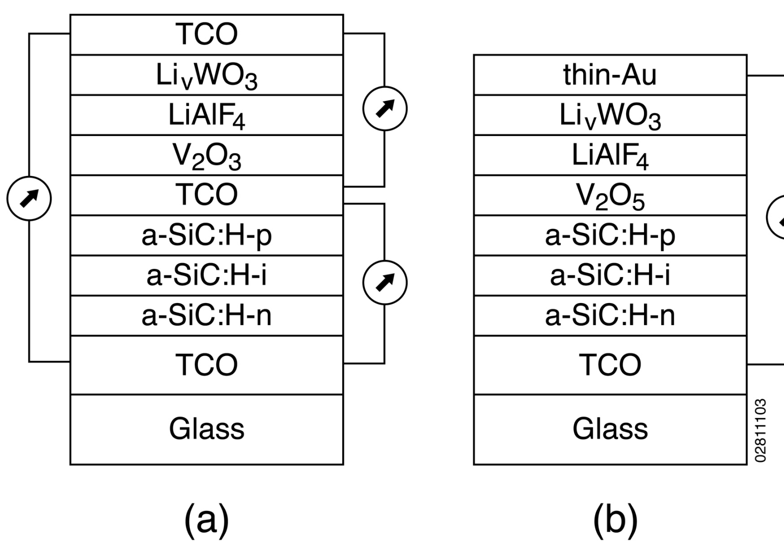

Figure. 3 (a) Target structure of a PV-ECW device. The upper half is the ECW and the lower half is the PV. The middle contact permits battery and user control; (b) Devices structure in this study. When the top and the bottom conductors are connected, the device darkens.

To realize a monolithic PV-ECW structure, the device has to be well designed. Each of the nine layers of the tandem device as shown in Fig. 3(a) must be optimized to obtain good device performance. In Fig. 3(a), our target design, transparent conducting oxide (TCO) is used for each conducting layer to maximize the device transmittance. By connecting three conducting layers through a battery and a controlling circuitry, the device could be fully controlled by the user in the manual mode or automatically controlled by external circuitry. When the device is colored under the light, the top and bottom TCO's are connected by an external wire. When the coloration processes stopped, extra energy generated by the PV device could be stored in a rechargeable battery via connecting the middle contact. This energy could be used to bleach the EC device when necessary.

In Fig. 3(b), our current device structure, a middle contact layer is removed and semitransparent gold is used as the top contact instead of TCO. We used gold as the top electrode to save time and improve reproducibility during our preliminary fabrication processes. The middle contact was removed to avoid the shorting problem temporarily and to still be able to stack the PV-ECW device together so that important features of the device could be studied.

Fig. 4 shows the transmittance spectra of a 16- cm^2 monolithic PV-ECW device with the structure of Fig. 3(b). It is colored by short-circuiting the top and bottom transparent electrodes under 1-sun illumination, and is bleached by applying 2 V with respect to a forward bias for the PV device. These spectra are shown in the two upper curves of the Fig. 4. The bottom curve shows a more deeply colored state obtained by applying 0.6 V of external coloring voltage to augment the 1-sun PV voltage. Our PV-ECW device shows a relative transmittance change of more than 60% at 670 nm under 1-sun illumination, and an 80% change when the small external voltage is applied. Its color is pale yellow at bleached state and dark blue at colored state. The deeper coloration with the external voltage source indicates the potential of improving the device contrast either by applying higher PV voltage or designing the EC device to maximize the lithium concentration in the electrochromic material during coloration. The absence of a middle conductor in this developmental device required that both coloring and bleaching current flow through the PV and EC device all the time. Therefore, the 2-V bleaching voltage includes the part required to overcome a built-in potential from the PV device (about 0.8 V). In the final retrofit smart-window structure, a middle contact layer will be inserted, which allows more user control and the option of PV battery charging.

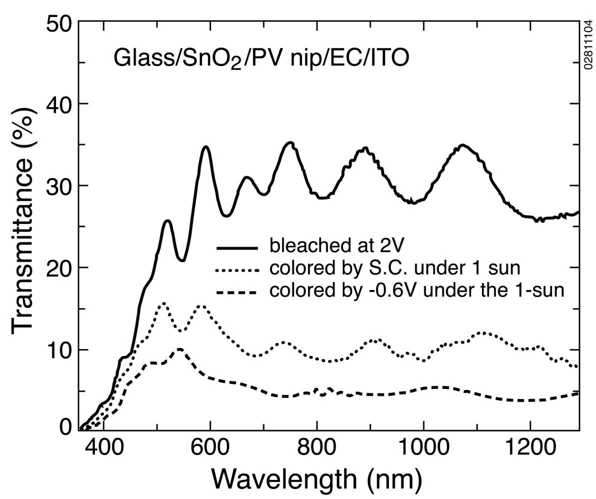

Figure 4. Transmittance spectra of a monolithic PV-ECW device

A NOVEL PHOTOELECTROCHROMIC DEVICE

A dye-sensitized solar cell electrode was recently combined with an electrochromic film to produce what we called a "photoelectrochromic" window [Bechinger et al., 1996]. Due to the complementary nature of the two technologies, we were able to combine just one-half of a typical dye-sensitized solar cell with one-half of a typical electrochromic cell. The electrochromic film was deposited on the counterelectrode of a dye-sensitized solar cell and lithium ions were added to the electrolyte solution. The I_2 required in the electrolyte for high-power solar cells was eliminated in order to maximize the photovoltage, and a low concentration of a more transparent dye was employed as the sensitizer. In this configuration, the photovoltage produced by the dye-sensitized electrode drives electrons and compensating Li^+ cations from the WO_3 film, resulting in a colored electrochromic film. When illumination ceases, the potential of the charged WO_3 film causes the coloration process to reverse, expelling Li^+ from the WO_3 film and transferring electrons, via the external circuit, back to the oxidized iodine species in solution.

CONCLUSIONS

Several innovative approaches are being taken to develop self-powered PV-EC window devices for energy-saving applications. They are (i) stand-alone, side-by-side PV-powered electrochromic smart windows; (ii) monolithically integrated PV-EC window devices; and, (iii) a novel photo-electrochromic device based on dye-sensitized TiO_2 solar cells. The compatibility of PV-EC devices has been analyzed and the potential for large energy savings for building applications has been indicated. The technical feasibility of various design options has been demonstrated. However, many technical barriers must be overcome before some of these technologies can find their way to the marketplace.

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